Beacon Monitoring Approach to Spacecraft Mission Operations

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Abstract

A tic\+' tec)~ttoIogy dc~)cloi)ttlett ieffot[is underway at JPL that merges new technologies for automating spacecraft functions with a new concept for mission operations. This technology, commonly referred to as beacon monitoring, is a process for eliminating the ground to spacecraft telemetry link during periods of routine operation. The goal of this new approach is to significantly reduce the size of flight project operations teams to lower cost. With beacon monitoring, one of four possible beacon "tones" will initiate ground response actions based on the spacecraft 's assessment of its own state as determined by onboard autonomy. When an event Oc('ills requiring ground intervention, the spacecraft will transmit intelligent telemetry summaries to quickly provide operators the necessary context information. As appropriate, ground personnel will be able 10 access telemetry, disable onboard autonomy, and command the spacecraft for anomaly resolution or to perform routine maintenance

This paper provides an overview of beacon monitoring and the process for developing and infusing the technology into flight project mission operations and spacecraft designs.

1.0 introduction

The Jet Propulsion Laboratory has a long history in developing and operating "autonomous" robotic spacecraft. Autonomy in this traditional sense has largely pertained to redundancy management and alarm threshold-based spacecraft fault protection. For some time, mission operations engineers and software. technologists at JPL have been evolving a new vision which will result in onboard functionality that allows the spacecraft to become de-coupled from the ground most of tbc time. Advances in mission development processes, computing hardware and the maturity of artificial intelligence techniques have been the primary technical enablers for this approach. A willingness on the part of NASA to invest in technology that substantially reduces operations costs has been the programmatic enabler.

The autonomy vision, however, was somewhat bl urry until about a year ago. As the Pluto Express mission operations concept evolved, a new millennium vision for "darkening the skies" with inexpensive. robotic spacecraft early in the next century was set forth by NASA. Now, in addition to the need to reduce mission operations cost, was the realization that existing ground station tracking resources may prove inadequate to handle large numbers of missions. The end result has been a new technology concept for mission operations called *beacon monitoring*.

2.0 Beacon Overview

Beacon monitoring represents a significant departure from the way mission operations has typically been performed within NASA, With beacon monitoring, the spacecraft is given the authority to initiate interaction with the ground only when required. Although still fully accessible, the spacecraft will be engineered to be much more self-sustaining and will be capable of analyzing all engineering measurements onboard (luring periods of routine operation. On-board adaptive sequencing, data collection, and performance analysis will place the spacecraft in the best position to know when ground interaction is required. Beacon monitoring is a process for interacting with this level of autonomy. When beacon monitoring is used, one of four possible messages will be selected by onboard software and transmitted to the ground in the form of subcarrier tones or other signals that can be detected by the ground without the need for large aperture deep space antennas or elaborate symbol synchronizers, bit detectors, convolutional decoders, etc. The four spacecraft beacon monitor messages will be:

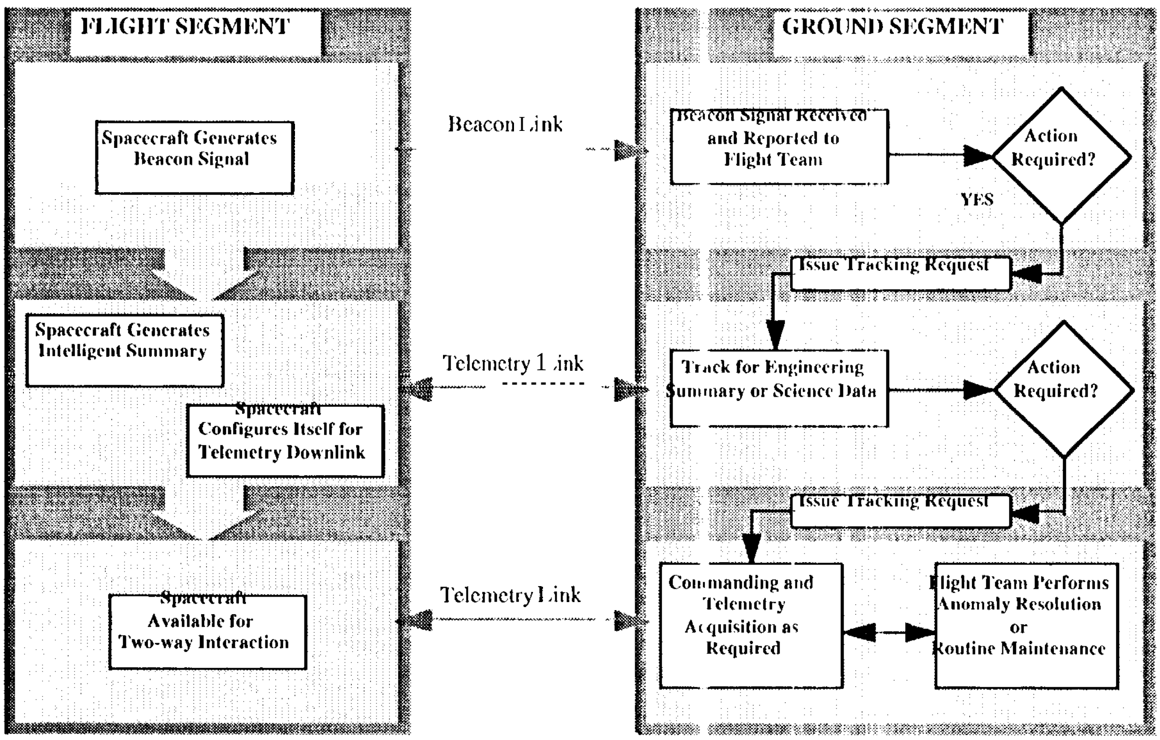
1--[GREEN] I'm OK and don't require any ground interaction at this time. Check On me again tomorrow.
2--[RED] I am in an emergency mode and require ground interaction as soon as possible.
3--[ORANGE] I require ground interaction sometime in the next few days, so 1 can downlink data stored cm-board which otherwise will exceed storage capacity and be overwritten.
4-[YELLOW] I do not require any ground interaction, but I have information that you may be interested in having me downlink earlier than the next scheduled track.

When necessary due to onboard events, intelligent summaries of engine.cring data will be downlinked to rapidly provide context information to the project flight team. If farther interactions are required, the project team will be able to receive additional telemetry and send commands to the spacecraft.

End-to-end Process

The end-to-end Beacon Monitor process can be represented as a flowchart showing functions performed on the spacecraft and ground segments. The flight segment functions are implemented in software while the ground segment functions are represented as a combination of software and "people" procedures. Figure 2.1 represents the "sttaw'll]arl''proccss for bc.aeon monitoring. For

Figure 2.1
Strawman Beacon Monitoring Process



periods in which beacon monitoring is used, the spat.ccraft will generate a beacon "tone" which will be received on the ground by the beacon monitor service and relayed to the flight team. This may be handled each clay as an mail message, an internet bulletin board, or via a simple phone call to the flight team. If the beacon message indicates that the spacecraft is requesting further interactions with the ground, a telemetry track will be scheduled and commands uplinked to direct the spacecraft when to begin transmitting engineering summary or stored science data. At this point, the flight project team will analyze the downlink data and determine if further actions are required. If the spacecraft must be commanded from the ground or if more data is required in order to analyze an onboard anomaly, another tracking request will be issued and the spacecraft will be fully commandable.

Flight Software Components

Describing flight software components provides additional insights into tbc beacon monitoring concept. It is important to realize that although beacon monitoring is enabled by --and forms a portion of -- a ncw vision within NASA for spacecraft autonomy, the overall concept should be generally applicable to missions with enhanced onboard automation capabilities.

Beacon Tone Generation

When beacon monitoring is used during a mission, the spacecraft will continuously transmit a beacon signal to the extent possible given mission activities. A beacon software "layer" will be infused into the overall autonomy architecture and will be responsible for providing the highest level of spacecraft state assessment and will send the appropriate message to set the frequency of the. beacon transmitter.

At JPL, mission operations engineers and software technologists are generally assuming the four-mode system. The notion that the.rc nerds to be a small number of tones to limit the operations response space has been gaining acceptance even though the temptation is often 10 provide spacecraft state information by adding more modes. Having projeet-definable modes is also an option and adds flexibility to the overall concept. It makes sense that a project may use beacon monitoring differently during different mission phases and that different types of missions are likely to have different uses for the beacon

Engineering Summary

The goal of engineering summary data is to quickly provide context information to tbc flight team when ground interactions are required. Defining this capability is a formidable task and is itself a novel component within the overall technology. Advanced anomaly detection methods [1] are expected to have a role in engineering summary formulation. Figure 2.2 illustrates bow engineering summary data fits into the overall monitoring process and highlights some of the key differences between beacon monitoring and traditional operations.

Figure 2.2
Role of Engineering Summary
within the Beacon Monitoring Process

Engineering Analysis Task	Old Paradigm	Beacon Paradigm
Status	Routine telemetry downlink	Beacon tone
Engineering performance Analysis	Routine telemetry downlink	Engineering summary telemetry
Engineering archive analysis	Routine telemetry downlink	Telemetry downlink as file transfers

Although still in the early stages of development, initial brainstorming has provided insights into the types of information that should be computed onboard for inclusion into these summaries. The capabilities of onboard autonomy should enable a highly flexible, adaptive summary capability to be implemented. Figure 2.3 lists some of the candidate components. It is likely that spacecraft state infer-lllation, a telemetry summary, and possibly full-frame telemetry will be concatenated together to form each summary. The scope of onboard conditions and link constraints will determine how much information is provided in each of these three areas.

Figure 2.3
Components of 1 ingineering Summary

Spacecraft Stale Information
•Spacecraft muck information
•command 1 .og
•live.nt I .og
•Data providing insights into onboard inferencing
Telemetry Summary
• Snapsh ot telemetry
• Slow Trends
•Statistical Summaries
• Telemetry data (lossy compression)
FuN Frame Telemetry
● Scnsur data causally related to sensors detecting an anomaly or significant event
•Ancillary information to support playback
•Other full-frame engineering telemetry

Fall-back Capability

Spacecraft that use beacon monitoring must be capable of operating in deterministic, non-automated modes as well as in automated modes. Designing for effective fall-back capability is largely a system engineering problem resolvable during development. At the heart of a fall-back capability is the ability to disable autonomy. An example of this might be specifying hierarchies of rule priorities during development so that individual, or classes of autonomy rules, can be de-activated during anomalies and during ground-based troubleshooting or for particular mission activities or phases. This is an essential fault protection consideration as well as an operability issue for spacecraft systems that use a rule-based approach to onboard autonomy.

Ground Tracking

Beacon tones could be implemented as modulated subcarrier signals. With such an approach, a spacecraft may be assigned a unique carrier frequency and the subcarriers (beacon tones) would correspond to known offsets from that carrier frequency. Since the scheme must handle many spacecraft, it has been proposed that each spacecraft could have a u n iquc carrier frequency.

The ground station antenna size is a function of the transmitter radiated power, the s/c antenna size, the s/c antenna pointing accuracy, anti the maximum distance imposed by the spacecraft trajectory. Since no data (telemetry) acquisition occurs, the ground antenna receiving the beacon signal can be smaller because the signal can be integrated over longer periods of time., Also, for beacon monitoring, the s/c can be flown in a wider limit cycle deadband than for telemetry downlink, providing savings in attitude control gas.

Designers must also consider data rate reduction as a function of spacecraft distance from earth. This is a key issue in determining the quantity of engineering or full-frame telemetry data that can be downlinked in the amount of tracking time available. in fact, intelligent engineering data summaries should be assembled with this consideration in mind.

Mission Operations

For long duration missions involving complex spacecraft, the cost of mission operations can exceed development cost [4]. Beacon monitoring technology brings with it two mechanisms for reducing cost. The capabil ities of new onboard technologies can perform functions that would normally be performed on the ground. Reducing the types of tasks that mission operators perform will reduce mission operations costs *[4]. The* other cost saver is the fact that with beacon monitoring, operators wiii only be called in on demand, resulting in an entirely new staffing approach.

To illustrate the point, one can think of traditional mission operations as “continuous intensive care.” Beacon monitoring will enable a staffing profile more akin to an “emergency room,” where the patient (the spacecraft) does not require any assistance unless it believes itself to be unhealthy.

The cost savings from such an approach appear to be straightforward, but emergency room staffing introduces some issues that must be dealt with in defining a mission operations approach. Perhaps most importantly, a transition to beacon monitoring should only occur after the mission operations team has built a base of experience with a spacecraft, This is likely to occur anyway during the period in which lint-launch checkout takes place. Still, it is important that the operators learn the peculiarities of a given spacecraft.

Another concern is that operators could become rusty without having routine interactions with the spacecraft and would not be able to diagnose anomalies at an appropriate level of proficiency. Training is another concern. The problem here lies in how to bring in new operators without on-the-job training.

Simulations bold promise as being a solution for many of the staffing issues that must be resolved for beacon monitoring to be effective. One vision is to evolve simulations throughout development and transition them into operations to support training, and troubleshooting analysis. These simulations would have a fault injection capability and would adapt to match the behavior of the spacecraft throughout the mission.

Another consideration, partially contingent cm the requirements of simulations, is the need to poll the spacecraft periodically for engineering archive telemetry during times when all conditions arc nominal and the beacon mode is "Green." Although the simulations may not be exactly operating in parallel with the spacecraft, there is likely a need to periodically synchronize the simulation with the actual spacecraft to adequately model slow trends in certain behaviors.

3.0 Technology Development

Most of the time at JPL, technology development efforts are funded, especially in the early stages, by the R&D organizations within NASA. introduction and funding of this technology began both in flight project (actually the Pluto Express pre-project) community and the research communities at JPL. The approach taken so far has been to work toward developing a widely applicable yet consistent technology for cruise phase beacon monitoring for use on future space missions. Diverse funding should enable evolution of this type of general solution,

Development Process

Beacon monitoring is partially enabled by new approaches to technology and mission development, Concurrent engineering, which has been defined as "...the simultaneous development of two or more interacting systems from the earliest stages of the system life cycle through the design and development process" [3], provides the basis for effective development of this end-to-end technology. Rapid prototyping, evolutionary development processes, and testbedding in conjunction with concurrent engineering reduce the risk and possibly the cost of developing this new technology. Another important dimension to beacon monitoring development is successful coordination with relevant projects and programs.

Beacon monitoring technology development can be broken down into five primary deliverables. Shown in Figure 3.1, each deliverable signifies a milestone in technology readiness. NASA describes technology maturity using Technology Readiness Levels (TRL's). [2] Tasks supporting the each deliverable will yield "evolutionary" demos hat will be continually refined. Hence, TRL's are shown as a range with the upper bound serving as the rating for the final deliverable.

Figure 3.1
Mission Development Deliverables

Deliverable	TRL
Concept description	1-2
Ground-based technology demo	3-5
Simulated flight experiment	5-6
Flight experiment	7-8
Full-up use on a flight project	9

The development philosophies outlined above are likely to play a key role in successful development and infusion of the technology for beacon monitoring. Proposed missions described more fully below, seem to be using these approaches so far in development activities. Such uniformity is likely to make sharing of technologies and prototypes across projects easier, further reducing development cost.

Infusion into JPL Flight Projects

The technology infusion process witbin NASA has been described as a combination of "technology push" and "mission pull." [2] This appears to be happening as upcoming missions arc expressing an interest in the technology for beacon monitoring and the supporting technologies for spacecraft autonomy.

Pluto Express

As previously mentioned, Pluto Express has been instrumental in developing the technology. Pluto Express, with its long duration interplanetary cruise, is an ideal mission for full-Up use of beacon monitoring. Ironically, though, it is at the end of the flight opportunities pipeline and it is likely that the capability will be flight-demonstrated sometime prior to the Pluto Express launch. Early demonstration will reduce. Pluto Express development risk and will better insure that the capability can be successfully exploited during Pluto Express cruise phase.

Pluto Express recognizes and plans on leveraging outside development efforts, but also considers internal development funding essential to reduce technical and programmatic risk. ongoing evolutionary prototyping activities that support beacon monitoring and demos are planned for this year to illustrate the concept. Initially, the prototype will demonstrate only toot selection by 'firing' spacecraft autonomy rules based cm simulated telemetry values. The next step will be to develop an early form of onboard intelligent engineering summary. Over the next year, emphasis will be placed on developing tbc engineering summary technology component, Prototypes will continue to evolve and the results of outside efforts will be infused as appropriate throughout development.

New Millennium Program

This effort grew out of the new NASA vision for "darkening the skies" with spacecraft and manifests three near-tcnn J]'], missions. The program is organized through integrated Product Development Teams (1 PDT"s) which are to suppl y each flight project team with new technologies. Beacon monitoring is considered a priority within the Autonomy 1 PDT and a flight experiment is under development with tbc first New Millennium flight as the target demonstration opportunity.

OPSAT

OPerations SATellite, O] 'SAT, is a proposed low-cost NASA mission for flight demonstrating beacon monitoring and other technologies for reducing the cost of mission operations. This mission concept grew out of a realization among mission operations technologists that the science-driven nature of most NASA missions limits the amount of risk that can be taken and has tended to place mission operations staffing concerns at a lower priority. Although this attitude is changing due to ever increasing pressure to lower cost, a strong need exists to highlight beacon monitoring and other technologies for low-cost operations. All aspects of the cad-to-cod capability for beacon monitoring would be developed. The OPSAT flight team would validate the technology and would actually demonstrate low cost mission operations through reduced staffing levels.

4.0 Acknowledgments

The technology described in this paper has been developed at tbc J et Propu 1 si on Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration. This concept originated with a vision for Pluto Express mission operations conceived by John Carraway. Jay Wyatt has been involved in developing various aspects of beacon monitori ng and initially presented the concept for use on the New Millennium Program. Bruce Crow has developed a comprehensive approach for Deep Space Network suppoi i of beacon monitoring. Richard Doyle has provided artificial intelligence technologies that support vai ions aspects of the concept. Don Sweetnam has stimulated discussion on the appropi iate numbei of beacon tones for the beacon monitoi ing and is co-lead of the OPSAT mission proposal, Gael Squibb has facilitated development of various aspects of the capability and has contributed to discussions that have refined the operations concept.

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